

# **CELL ARRAY AND METHOD OF MULTIREOLUTION MOTION ESTIMATION AND COMPENSATION**

## **CROSS-REFERENCE TO RELATED APPLICATION**

[0001] This application claims priority under 35 U.S.C. § 119(e) to co-pending U.S. Provisional Patent Application No. xx/xxx,xxx, Attorney Docket No. 22682-06234, entitled "Video Processing System with Flexible Video Format," filed July 31, 2001, the subject matter of which is incorporated by reference in its entirety herein.

## **TECHNICAL FIELD**

[0002] The present invention relates generally to video processing, and in particular to a video encoding compression scheme used with motion estimation and compensation.

## **BACKGROUND OF THE INVENTION**

[0003] Conventional video compression algorithms utilize the temporal correlation amongst frames of pictures to remove redundancy there between. For example, a previous (reference) frame is used to predict a current frame to be encoded. The prediction operation must account for the motion of objects in a frame in order to enable motion compensation, whereby a matchblock is taken from a current frame and a spatial offset in the reference frame is determined to represent a good prediction of where the matchblock of the current frame can be found. This offset is known as the motion vector. To determine the spatial offset, some form of difference is taken between a search area of the reference frame and a matchblock of the current frame to generate the prediction data. -

[0004] In general, motion compensation involves the use of the motion vector to extract the predicting block from the reference frame, to subtract it therefrom, and to use the resulting difference for further compression. Motion estimation involves ascertaining the best motion vector to be used in predicting the matchblock from the current frame. In the typical model used for motion estimation, an assumption is made that the image in the current frame is a translation of the image in the reference frame. It can be also assumed that there is virtually no change in the image content amongst frames, or that such a change will be compensated by known techniques not specifically discussed herein. Because the image of the current frame is a translation of the image of the reference frame, a block of pixels in the current frame must reside somewhere within a searchable area in the reference frame.

[0005] One problem associated with motion estimation is that it is an expensive computing activity in the encoding process, i.e., typically associated with calculation intensive steps. For example, in FIG. 9, for each match, exhaustively searching a (64 x 64 pixels) search area 122 for a (16 x 16 pixels) matchblock 120, involves undertaking: 256 comparisons (differences); 256 calculations involving computing the absolute values of the differences (referenced subsequently as "absolute value calculations" for convenience and brevity) between the matchblock and a search area; and 255 additions of the 256 values. For 64 matches, the total computations involved increases drastically to  $64 \cdot 64 \cdot 256 + 64 \cdot 64 \cdot 256 + 64 \cdot 64 + 255$ . Because motion estimation conventionally requires an exhaustive search of a large area of the matchblock, it can

thus be appreciated that a need exists for a technique to reduce the number of computations required to determine the motion vector information. It is desirable to reduce the large number of calculations traditionally involved to determine the motion vector.

[0006] In the past, approaches aimed at reducing the large number of calculations associated with motion estimation have generally proven unsatisfactory because of the degradation in resolution quality. For example, to reduce the large number of calculations, one conventional approach increases the size of the matchblock. This increases the computations per comparison; however, there will be fewer blocks per frame, which leads to a lower number of times motion compensation is undertaken. While this approach results in fewer blocks per frame, it is problematic because it can lead to poor predictions, especially when the probability that a block will contain objects moving in different directions increases with size. Another approach attempts to reduce the search area size in order to reduce the number of computations to search for a match. Yet, this approach has a drawback of missing the match because the search area is small. Accordingly, what is needed is a way to reduce the number of motion estimation calculations while keeping a high quality of the resulting predictions. It is desirable if the motion estimation calculations could improve the resolution quality of the resulting predictions.

[0007] When the video compression techniques and associated hardware are applied in the field of portable multimedia devices, other considerations arise. To be practical and cost-effective, the architecture hardware must not only be able to handle a large amount of data traffic

as a result of the intensive calculations associated with video processing, but also be compact and uncomplicated. The large amount of data traffic is a result of loading video images from storage to a processor, and returning the processed images back to storage, only to load more video images. Conventional approaches use a 128 bit bus to handle the large amount of data traffic, however, this data bandwidth is too large for the minimal placement and routing requirements of VLSI, ASIC and System-on-Chip (SoC) applications being used in increasing smaller and more streamlined multimedia-based devices and appliances. As many hand-held portable devices equipped to handle multimedia video formats continue to become increasingly smaller in size, it would be ideal if the video compression hardware were streamlined, that is, with logic designed so that the routing, placement, and layout of logic and circuit components are compact, have an uncomplicated design, and yet are enabled to accommodate complex calculations.

#### **SUMMARY OF DESCRIBED EMBODIMENTS**

[0008] The present invention overcomes the deficiencies and limitations of the prior art by providing a system for video compression of frames of pictures (images). According to one aspect of the present invention, a novel system for performing motion estimation and compensation is provided. In order to determine the motion vectors used in motion estimation, one embodiment of the system includes a base platform (back end) having a processor, bus and interrupt controller, memory device, memory controller, and multi-channel controller coupled to a system bus. Digitized video signals originating from a source are received by an audio/visual

input interface which is coupled to the system bus. In the embodiment described, the system further includes a front end having a discrete cosine transformer capable of functioning also as an inverse discrete cosine transformer, quantizer capable of functioning as an inverse quantizer, a variable length coding encoder, macroblock SRAM, a stream buffer, one or more block SRAMs generally functioning as buffer memories, and a motion estimation and compensation (MEC) engine.

[0009] The MEC engine includes a two-dimensional processor array (referred to as the MEC cell array) comprising a sub-array of p\_cells communicatively coupled to boundary cells. The boundary cells include io cells, updown cells, and column cells. In one aspect in accordance with the present invention, the MEC cell array is configured with a Multiple Input stream Multiple Data stream (MIMD) arrangement of control signal lines, and is operated by a column controller, and two integrated circuit (IC) controllers, namely an x-instruction controller and a y-instruction controller which control the operation of the two dimensional processor array. The column controller is the last processor which decides the optimal motion vector to output.

[0010] One benefit of using the MIMD arrangement is the multiple processing functions enabled in the cell array, wherein each cell is capable of processing its own set of instructions simultaneously and independently. With the MIMD arrangement, the MEC cell array is enabled to perform video processing, thereby allowing the system (back end) processor to provide the control and coordination of blocks of data.

[0011] Another aspect in accordance with the present invention includes the MEC cell array being configured with a Single Input stream Multiple Data stream (SIMD) arrangement of control signal lines operated by the system (back end) processor.

[0012] According to a further aspect of the present invention, the p\_cells of the MEC array are capable of holding several groups of Q pixels from an M x M block of pixels, wherein  $Q < M$ . In particular, the p\_cells can hold Q pixels from a matchblock, Q pixels from a reference block, and Q pixels from the predicted data block. With one particular implementation of the present invention,  $M = 16$  and  $Q = 4$ .

[0013] In another aspect in accordance with the present invention, the boundary cells enable the storage of data that has moved outside the boundaries of the sub-array. By storing such data in the boundary cells, the MEC cell array can readily obtain such data when needed. This improves processing speed because the data stored in the boundary cells do not need to be retrieved from external storage, which is typically associated with longer access times. Additionally, the boundary cells are beneficial in increasing the overall size of the cell array, and this increased size provides further improvement to the amount of data that can be processed. This is particularly useful for VLSI, SoC and ASIC applications, which typically have increasingly small "real-estate," that is, chip area and size.

[0014] The present invention overcomes the limitations of conventional video processing systems by using an MEC array having a simple design, routing and placement of logic and

circuit components. By duplicating a small amount of random logic (i.e., the p\_cell) to form the sub-array, a larger cell array can be easily achieved based on simple interconnections coupling together adjacent p\_cells. By introducing this MIMD architecture in the cell array, the capability of handling complex instructions and processing is further achieved. One advantage of the present invention is that data traffic is minimized according to one embodiment of the present invention, which utilizes a 36 bit bandwidth. This is beneficial for VLSI, SoC and ASIC applications.

**[0015]** The video compression system in accordance with the present invention also includes a method of motion estimation and compensation processing, overall having three stages of multi-resolution searching, followed by YUV estimation and decompensation. In the first stage, the method includes the determination of a set of partial motion vectors each associated with groups of pixels forming a given picture. A partial pixel level search is performed on sub-blocks of pixels, formed from decomposing the matchblock of the current frame into  $Q \times Q$  sub-matchblocks, and from decomposing the search area of the reference frame by a similar factor. Exhaustive  $Q \times Q$  searches are performed in parallel on each decomposed matchblock which is duplicated and overlaid with each corresponding decomposed search sub-block in order to determine a preliminary motion vector.

**[0016]** In the second stage, the method further includes the generation of an intermediate (full) motion vector having finer granularity than the preliminary motion vector. To do so, a full

pixel level search of the full size macroblock is performed around an area of the preliminary motion vector. Because the macroblock has already been loaded in the MEC cell array during the partial pixel level search, only a refined area need be loaded into the cell array, thereby saving overall processing time.

[0017] With the third stage, the method comprises performing a fractional (e.g., half) pixel search using the results of the full pixel level search. In particular, the full size macroblock is searched with a refined search area based on the full pixel level search to determine a final motion vector of improved granularity.

[0018] One aspect in accordance with the present invention is that the three stages of multi-resolution search method results in a motion estimation and compensation algorithm that is fast because it involves less computations than conventional methods. The algorithm is also fast due to the parallel processing of the motion vectors undertaken in the MEC cell array, and contemporaneously with preloading of data in the stream buffer. Another aspect in accordance with the present invention entails the method improving the quality of the motion estimation by incrementally refining the motion vector throughout the three stages. As a result, the calculation intensive steps associated with the conventional encoding process are substantially reduced with the present invention.

[0019] In general, the present invention takes advantage of temporal redundancies amongst frames by undertaking block-based differences between frames of current and reference images



that have been split equally into several sub-blocks. For each sub-block, a search is performed for similar blocks in a reference frame, which also has been sub-sampled by a factor of Q. With the MEC cell array, parallel processing of a plurality of these Q x Q sized sub-blocks is enabled.

[0020] The features and advantages described in this summary and the following detailed description are not all-inclusive, and particularly, many additional features and advantages will be apparent to one of ordinary skill in the art in view of the drawings, specification and claims hereof. Moreover, it should be noted that the language used in the specification has been principally selected for readability and instructional purposes, and may not have been selected to delineate or circumscribe the inventive subject matter, resort to the claims being necessary to determine such inventive subject matter.

#### **BRIEF DESCRIPTION OF THE DRAWINGS**

[0021] The teachings of the present invention can be readily understood by considering the following detailed description in conjunction with the accompanying drawings.

[0022] FIG. 1A is an illustration of various exemplary applications that work suitably well with the video processing system in accordance with the present invention.

[0023] FIG. 1B is an illustration of additional exemplary applications of FIG. 1A.

[0024] FIG. 2 illustrates a block diagram of one embodiment of a video processing system in

accordance with the present invention.

[0025] FIG. 3 is a detailed block diagram of a particular embodiment of the motion estimation and compensation (MEC) engine of FIG. 2.

[0026] FIG. 4 is a block diagram of a particular embodiment of the cell array for the MEC engine of FIG. 3.

[0027] FIG. 5A is a data flow diagram of a particular implementation of control signals for the MEC cell array according to an MIMD arrangement.

[0028] FIG. 5B is a data flow diagram of an alternate implementation of control signals for the MEC cell array according to an SIMD arrangement.

[0029] FIG. 6 is a flowchart showing one implementation of a method of motion estimation and compensation processing in accordance with the present invention.

[0030] FIG. 7 is a flowchart showing a detailed implementation of the method of motion estimation and compensation processing of FIG. 6.

[0031] FIG. 8 is an illustration of a set of pixels and corresponding fractional pixel locations.

[0032] FIG. 9 is an illustration of a matchblock overlaid with a search area of a reference frame for performing an exhaustive search.

[0033] FIG. 10A is an illustration of duplicated  $Q \times Q$  (subsampled) sub-matchblocks overlaid to perform parallel exhaustive partial pixel level searching of search area sub-blocks in accordance with the present invention.

[0034] FIG. 10B is an illustration of a refined search block for performing full pixel level searching in accordance with the present invention.

[0035] FIG. 10C is an illustration of a further refined search block for performing fractional pixel level searching in accordance with the present invention.

[0036] The figures depict a preferred embodiment of the present invention for purposes of illustration only. One skilled in the art will readily recognize from the following discussion that alternative embodiments of the structures and methods illustrated herein may be employed without departing from the principles of the invention described herein.

## **DETAILED DESCRIPTION OF EMBODIMENTS**

### **INTRODUCTION**

[0037] A system, method, computer medium and other embodiments for video encoding, motion compensation and improving motion estimation are described. In the following description, for purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the invention. It will be apparent, however, to one skilled

in the art that the invention can be practiced without these specific details. In other instances, structures and devices are shown in block diagram form in order to avoid obscuring the invention with unnecessary details.

[0038] Reference in the specification to "one embodiment" or to "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiments is included in at least one embodiment of the invention. The appearances of the phrase "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment.

[0039] Some portions of the detailed description that follow are presented in terms of algorithms and symbolic representations of operations on data bits within a computer memory. These algorithmic descriptions and representations are the means used by those skilled in the data processing arts to most effectively convey the substance of their work to others skilled in the art. An algorithm is here, and generally, conceived to be a self-consistent sequence of steps (instructions) leading to a desired result. The steps are those requiring physical manipulations of physical quantities. Usually, though not necessarily, these quantities take the form of electrical, magnetic or optical signals capable of being stored, transferred, combined, compared and otherwise manipulated. It has proven convenient at times, principally for reasons of common usage, to refer to these signals as bits, values, elements, symbols, characters, terms, numbers, or the like. Furthermore, it has also proven convenient at times, to refer to certain arrangements of

steps requiring physical manipulations of physical quantities as (modules) code devices, without loss of generality.

[0040] It should be borne in mind, however, that all of these and similar terms are to be associated with the appropriate physical quantities and are merely convenient labels applied to these quantities. Unless specifically stated otherwise as apparent from the following discussion, it is appreciated that throughout the description, discussions utilizing terms such as "processing" or "computing" or "calculating" or "determining" or "displaying" or the like, refer to the action and processes of a computer system, or similar electronic computing device, that manipulates and transforms data represented as physical (electronic) quantities within the computer-based system memories or registers or other such information storage, transmission or display devices.

[0041] Throughout the description presented, reference will be made to the symbol "x" as indicating a multiplication operation, and as a description of the number of rows by the number of columns in an array, depending on the context. When the symbol "x" refers to a multiplication operation, the symbol "•" may be used interchangeably as will be recognized by those skilled in the art. In general, the context where the symbol "x" refers to the number of rows by the number of columns in an array arises in describing a block of pixels representing an image.

[0042] One aspect of the present invention includes an embodiment of the process steps and instructions described herein in the form of a computer program. Alternatively, the process steps

and instructions of the present invention could be embodied in firmware or hardware, and when embodied in software, could be downloaded to reside on and be operated from different platforms used by video processing systems and multimedia devices employed with real time network operating systems and applications.

[0043] The present invention also relates to an apparatus for performing the operations herein. This apparatus may be specially constructed for the required purposes, or it may comprise a general-purpose computer selectively activated or reconfigured by a computer program stored in the computer. Such a computer program may be stored in a computer readable storage medium, such as, but is not limited to, any type of disk including floppy disks, optical disks, CD-ROMs, magnetic-optical disks, read-only memories (ROMs), random access memories (RAMs), EPROMs, EEPROMs, magnetic or optical cards, application specific integrated circuits (ASICs), or any type of media suitable for storing electronic instructions, and each coupled to a computer system bus. Furthermore, the computers referred to in the specification may include a single processor or may be architectures employing multiple processor designs for increased computing capability. In one aspect in accordance with the present invention, a Multiple Instruction stream Multiple Data stream (MIMD) computer architecture will be described, wherein each processor operates to process its own set of instructions simultaneously and independently of others.

[0044] The algorithms and displays presented herein are not inherently related to any

particular computer or other apparatus. Various general-purpose systems may also be used with programs in accordance with the teachings herein, or it may prove convenient to construct a more specialized apparatus to perform the required method steps. The required structure for a variety of these systems will appear from the description below. In addition, the present invention is not described with reference to any particular programming language. It will be appreciated that a variety of programming languages may be used to implement the teachings of the present invention as described herein, and any references below to specific languages are provided for disclosure of enablement and best mode of the present invention.

**[0045]** Reference will now be made in detail to several embodiments of the present invention, examples of which are illustrated in the accompanying drawings. Wherever practicable, the same reference numbers will be used throughout the drawings to refer to the same or like parts.

**[0046]** FIGs. 1A-1B are illustrations of various exemplary applications in which the video processing system 10 in accordance with the present invention will work suitably well. Such applications include a high quality PC video camera 1 used for video conferencing or as a video recorder. Another application includes video capture boards 2, which may be enabled with MPEG-1, MPEG-2, MPEG-4, H.263 and H.261 capability. Yet another application includes a video capture box 3 which may be enabled with MPEG-1, MPEG-2, MPEG-4, H.263 and H.261 capability, by way of example. Video capture boxes 3 can also be used for time shifting

purposes. Still another application comprises an IP (Internet Protocol) –based remote video surveillance system 4 outputting MPEG-1, MPEG-2, MPEG-4 or other type of video format. One type of video format that works suitably well in accordance with the present invention is a WIS GO Stream format from WIS Technologies, Inc. of San Jose, California. In FIG. 1B, other applications that are well-suited for video processing system 10, include the following: (1) high quality video cameras 5 with full D1 broadcasting quality; (2) personal digital assistants 6 operable as a video camera or as a visual communication device; (3) mobile visual communication devices 7; (8) portable wireless telephones 8 enabled to operate with visual communication by MPEG-4 over CDMA; and (9) personal video recorders (PVRs) 9 also known as digital video recorders (DVRs), and STB, along with other devices providing a home video gateway, visual conferencing and multimedia communication. It will be appreciated by those skilled in the art that the above-mentioned types of applications are only examples, and that the video processing system in accordance with the present invention works suitably well with a wide variety of applications.

[0047] FIG. 2 illustrates one implementation of a video processing system 10 that may be used to perform the motion estimation and compensation processing in accordance with the present invention. One aspect of video processing system 10 includes video compression of moving images as part of an encoding process. From the discussion to follow, it will become apparent that the present invention is not limited to the system 10, but may work suitably well with other video processing systems and video compression systems. In the implementation of



FIG. 2, system 10 includes a processor-based platform 11 (back end 11), and a front end 13.

Data from source 12 is received by an audio/visual (A/V) interface 16. The AV interface 16 is synchronized with a pixel clock PCLK (not explicitly shown), which may be operating at a low frequency, like 27 MHz by way of example. A data (pixel) bus 14 allows the transfer of pixel data from the source 12 to the AV interface 16. Every clock cycle, a pixel can be input through the pixel bus 14 with a valid pixel signal. Those skilled in the art will recognize that the input timing can be controlled by horizontal and vertical synchronize signals.

[0048] The source 12 may be a multitude of devices that provide a digitized video bit stream (data stream), like for example, from a Complementary Metal Oxide Semiconductor (CMOS) device or Charge Coupled Device (CCD) sensor (with or without glue logic) like that used in a digital camera and PC camera. Other types of source devices that may work suitably well with the present invention, include by way of example, the Philips® 711x video digitizer and processor chip. By way of background information, in a digital camera, CCDs can be analogized to operating like film. That is, when they are exposed to light, CCDs record the intensities or shades, of light as variable charges. In the field of digital cameras, the charges are converted to a discrete number by analog to digital converters. It will be recognized that other types of sources capable of generating a digitized video bit stream may work suitably well with the present invention, including sources in the nature of a personal video recorder, a video-graphics capture and processor board, and a digital CAM recorder.

[0049] In general, source 12 generates an uncompressed video data bit stream 14, which may be of multiple formats. By way of example, the format of data stream 14 can comply with the CCIR (Consultative Committee for International Radio, now ITU-R) 601 recommendation which has been adopted worldwide for uncompressed digital video used in studio television production. This standard is also known as 4:2:2. Also, data stream 14 may be the parallel extension standard, namely CCIR 656 with PAL and NTSC, which had been incorporated into MPEG as the Professional Profile. CCIR 656 sets out serial and parallel interfaces to CCIR 601. Other suitable video formats include: YUV 4:2:2 interlace; 8-bit YUV with Vsync/Hsync/Fodd or Vref/Href format, interlace and progressive; 10-bit RGB Bayer with Vsync/Hsync CMOS sensor format. The support size can vary from 352x288 to 720x480 (30fps) or 720x576 (25fps), while the support input frame rate can vary from 10fps to 30fps. It is noted that these values are provided by way of example, and that the invention is not limited to these formats and parameters, but may work suitably well with other types of formats and parameters. When data stream 14 includes an audio component, the format of the data stream could also be in IIS (inter IC signal) format. Of course, the appropriate IIS data rates, which typically are at speeds of several Mbits/second, may be selected for transferring audio data. It will be appreciated that CCIR 656 and IIS are only examples of possible digital data formats, and that other formats are equally possible. A/V interface 16 includes necessary ports and circuitry to receive the incoming (video and/or audio) signals and to buffer data from such signals.

[0050] The base platform 11 is preferably a general microprocessor-based computing

system. In one implementation, the electronics of platform 11 are implemented as a single ASIC incorporating a processor 18, a system controller 20, memory device 22, memory device controller 24, a multichannel (e.g., Direct Memory Access DMA) controller 26, an input/output (I/O) interface 28, and an extensible program interface 30. In particular, the processor 18 may be any suitable processor with on-chip memory for encoding sub-sampled video signals, such as an Intel i860 pixel processor, programmed to implement the motion estimation and compensation techniques of the present invention. Preferably though and according to one implementation, processor 18 is a RISC-based CPU capable of controlling and coordinating the transfer of blocks of data, but not necessarily handling the video processing. By doing so, this keeps manufacturing costs of system 10 low, which is particularly beneficial when system 10 is utilized in VLSI, ASIC and System-on-Chip (SoC) applications. By way of example, suitable general parameters for choosing a low cost RISC CPU 18 include a 16 bit arithmetic logic unit (ALU), an 18 bit instruction set, and an operating speed up to 100 MHz. Exemplary applications suitable for the incorporation of system 10 include digital video recorders, remote video surveillance systems, video capture boxes, small portable handheld devices such as digital cameras, multimedia-enabled cellular phones and personal digital assistants (PDAs), and other media-based devices and appliances. The (XRISC) bus and interrupt controller 20 handles the workflow of the data and control signals for the computing processes of CPU 18, including for example, handling hardware and software interrupts, as well as those I/O signals generated.

[0051] Memory device 22 may be any suitable computer memory device for storing picture

data, such as a video random access memory (VRAM) or dynamic RAM (DRAM) device, under the control of memory device controller 24. Memory device 22 is shown as being external to platform 11 in FIG. 1, but may be integrated into platform 11 in other embodiments of system 10. In one embodiment where memory device 22 is a DRAM, controller 24 is selected to be a corresponding DRAM controller performing the physical transfers of data between the memory device 22 and the multichannel controller 26. In this embodiment, controller 26 may be a DMA controller selected to accommodate any suitable number of DMA channels used to transfer the retrieved video data into packed pixel format or planar bit maps, typically from the memory device 22 to each data block for processing by the MEC engine 38. By way of example, DMA controller 26 may use 8, 32 or any other number of channels, to transfer data from the DRAM 22 to each data block without necessarily utilizing the processing resources of CPU 18. In one embodiment, the DMA controller 26 is designed as a two-dimensional controller, operating on at least an instruction of pre-specified length, along with a start command, and source address. The multi-channel DMA controller 26 can include a plurality of channels, each with configuration registers holding information, such as the start address of data, the end address of data, the length of data transferred, type of stop transfer mechanism, and the source address of the data. Alternatively, the multi-channel controller 26 may facilitate the transfer of data from I/O block 28 to MEC engine 38, including by way of example, data from a host bus 21 coupled to I/O interface 28.

[0052] I/O interface 28 couples system 10 to various external devices and components,

referred to as hosts 25, using a variety of data standards and formats. For example, I/O interface 28 can include an output format along host bus 21 compatible with: a Peripheral Component Interconnect (PCI) bus typically having a wider bandwidth than the traditional ISA bus, and allowing peripherals to transfer data at higher speeds; a Universal Serial Bus (USB) hardware interface for low-speed peripherals such as the keyboard, mouse, joystick, scanner, printer and telephony devices, and also MPEG-1 and MPEG-2 digital video; IIC (inter IC control); and Host Parallel Interface (HPI). These types of ports in I/O interface 28 are only examples of possible port data formats, and other formats are equally possible. I/O interface 28 can be coupled to a variety of different hosts 25, including for example, PCs, applications supported by network enabled systems, servers, high quality PC video cameras for video conferencing, video recorders, video capture boards for MPEG-1, MPEG2, MPEG-4, H.263 and H.261, IP based remote video surveillance systems, video capture boxes for time shifting purposes, network computing systems, mobile visual communication, wireless communication by MPEG-4 over CDMA, and PDA enabled with multimedia features. Hosts 25 include driver level transcoding software to convert the compressed stream of data from I/O block 28 into MPEG-1, MPEG-2, MPEG-4, H.263 formats, by way of example.

**[0053]** Extensible program interface 30 enables data to be loaded into system 10 from flash memory device 32. A flash memory typically stores its content without the need for power, unlike a DRAM. Any number of suitable flash memory 32 devices may be used with the present invention, such as digital film in a PC card, a flash ROM, memory stick formats, and

SmartMedia.

**[0054]** The A/V interface 16, bus and interrupt controller 20 and multichannel controller 26 are coupled to one or both of a control bus 34 and data bus 36. According to one implementation, data bus 36 is a DMA bus. However, data bus 36 may be any suitable digital signal transfer device, including an Industry Standard Architecture (ISA) bus, an Extended ISA (EISA) bus, a PCI bus, or a VL bus. When data bus 36 is a DMA data bus, after initialization and during active capturing of the incoming video signal, DMA controller 26 requests the DMA bus 36 and, after acquiring the bus, will perform burst writes of video data to the memory 22 to be described further with MEC engine 38. In the particular implementation, databus 36 is selected to be 36 bits, which is a suitable width for VLSI, ASIC and SoC applications. It will be recognized that overflow handling capability can be designed with controller 26 in the event that excessive bus latency is experienced.

**[0055]** The front end 13 includes a motion estimation and compensation (MEC) engine 38 having a stream buffer (SB) 40 with a macroblock SRAM 60, discrete cosine transform (DCT) and inverse DCT (IDCT) module 42, buffers such as block SRAMs 41 and 43, a quantizer and dequantizer module 46, and a variable length coding (VLC) encoder 48. The MEC engine 38 and stream buffer 40 will be described below in more detail. The DCT/IDCT module 42 provides block-based orthogonal transformation of a block of picture elements to a matrix of spatial frequency coefficients in order to reduce spatial redundancy, typically after motion compensation

prediction or interpolation. By way of example, the internal accuracy of the DCT/IDCT module 42 can be 17 bits, with a DCT output saturated to 8 bits or 12 bits. Two aspects of the DCT/IDCT module 42 are to provide a very small error over the ideal floating model, and to reduce the mis-match of decoding function to be as small as possible. The quantizer/dequantizer module 46 provides further data compression when mapping the data to a representation that strips away unnecessary information, in general, based on zig-zag scans over the macroblock. The macro-block SRAM 60 is a memory device for storing the picture data used by front end 13. Block SRAMs 41 and 43 are shown as separate modules in FIG. 1, but may be part of the same component, and are generally used to store block data at various stages of the encoding process. Where the MEC engine 38 needs to share on-chip SRAM with other modules (e.g., DCT/IDCT 42), a programmable scheduler 21 can be included to coordinate the operation of various modules and processes in system 10.

[0056] In FIG. 2, a general block diagram is provided for the DCT/IDCT and quantization and dequantization functionality. Those skilled in the art will recognize that these functions may be provided in a variety of ways. For example, the output of the discrete cosine transform module 42 is quantized. An output of quantizer 46 can be reconstructed through inverse quantizer 42, and provided through inverse DCT 42 for storage in memory, like macro-block SRAM 60 so that it may undergo decompensation. The general purpose of subjecting the output of quantizer 46 through inverse quantization and inverse DCT 42 is to determine a difference macroblock that is lossy. When data is summed with the output of the MEC engine 38 along

with dedicated object-based motion prediction tools (not shown) for each object, a lossy version of the original picture can be stored in SRAM 44. Those skilled in the art will appreciate that motion texture coding, DCT-based texture coding (e.g., using either standard 8 x 8 DCT or shape-adaptive DCT) may also be provided with front end 11. It is noted that DCT/IDCT module 42 and quantizer/dequantizer module 46 not only provide the above functions during the encoding process, but is capable of emulating a decoder for the reconstruction of frames based on receiving the reference frames along with the motion vectors. To this end, the functional blocks 38-48 are capable of operating as a codec.

[0057] The VLC encoder 48 provides lossless coding to assign shorter code words to events occurring frequently and longer code words to events occurring less frequently. The use of a VLC is typically useful for reducing the number of bits used during encoding and video compression of motion data. The transform coefficients are quantized and the quantization label encoded using a variable-length coding.

[0058] Those skilled in the art will recognize that the blocks of FIG. 1 are functional blocks that may be implemented either by hardware, software, or a combination of both. Given the functional description of these blocks, those of ordinary skill in the art will be able to implement various components described using well-known combinational and/or sequential logic, as well as software without undue experimentation. Those skilled in the art will appreciate that the present invention is not limited to the video compression system described above, but is



applicable to any video processing system.

[0059] Reference is now made to FIG. 3 to further describe an embodiment of the motion estimation and compensation (MEC) engine 38. In the embodiment of FIG. 3, similar reference numerals are used for common components already described, primarily for convenience. The stream buffer 40 generally functions to manage access requirements from at least three different devices, that is, the MEC cell array 66, the DMA controller 26 and the DCT/IDCT module 42. It will be understood by those skilled in the art that the stream buffer 40 will require interfaces in order to communicate with these devices. For example, one interface connects the stream buffer with the DMA controller 26, another interface connects the stream buffer with the DCT/IDCT module 42, and yet another interface connects the stream buffer to the MEC array 66. One aspect of the stream buffer is to buffer the data loaded from the memory device 22 by the controllers 24 and 26. The data generally are organized in block type, wherein the block may include programmable x and y size. The stream buffer 40 will be read/written by the MEC array 66. The read and write instructions are typically burst with a programmable length, from a programmable start address, and by one of several predefined burst modes. It is advantageous to package the sequential data loaded from the memory device 22 to structures required by the MEC array 66 so that the order in which the MEC array 66 reads data can be different from the order in which data are read from the memory device 22.

[0060] In the particular embodiment shown in FIG. 3, the stream buffer 40 includes: an

SRAM 60 shared by the devices 66, 26 and 42; and a controller 62. SRAM 60 in one embodiment is 36 bits wide with a 1 Kbit word depth, thereby having a 36 x 1024 bit capacity with single port. Instruction RAM 64 is a storage cell (e.g., RAM, RISC file) that is accessed by the controller 20 for use by the CPU 18. The stream buffer 40 may include a register file that functions as a lookup table for converting all input logic address to its actual physical address. This lookup table can be accessed by the control bus 34. The XRISC controller may be designed to set the lookup table in the stream buffer through the appropriate interface, so that a host device may be able to read and write the SRAM cells through this interface.

**[0061]** The MEC engine 38 includes an MEC array 66 of cells 68. Databus 65 couples the MEC SRAM 60 to array 66, and can be 36 bits wide by way of example. Because array 66 comprises numerous cells 68, the data over bus 36 may be duplicated over lines 67, and received by appropriate cells 68. To facilitate this one-to-many mapping (databus 65 to datalines 67), it will be understood that an instruction may be provided from the XRISC controller 20 to indicate which cells accept (e.g., select) data over datalines 67. Datalines 69 carry the output from the cells 68 of array 66. The types of data that may be transferred from the stream buffer 40 to the MEC array 66 include pixel data, and the residue or predicted data of a matchblock or reference block. The types of data that may be transferred from the MEC array 66 to the stream buffer 40 include the predicted data, residue data, and the reconstructed data of the macroblock. Similarly, an instruction programmed by XRISC controller 20 may be used to select amongst datalines 69 the residual data to be transferred over databus 71. SRAM 60 also has inputs and outputs 73 and

75 (data port C) for communication of the residual information that has been further processed by the DCT/IDCT 42 (and quantizer 46) to finally optimize the compressed video stream.

[0062] The MEC array 66 is coupled to two IC controllers, namely an X-instruction controller 70 and a Y-instruction controller 72, as well as to an end column processor 74. X and Y instruction controllers 70 and 72 allow the XRISC controller 20 to configure an instruction set, and can be programmed to receive commands from controller 20. In response, the controllers 70 and 72 can make decisions and provide instructions (e.g., branch, jump) to the cells 68 of array 66. For example, the instructions may be 32 bits in length for the x control, and 24 bits in length for the y control. Each IC controller 70, 72 may include register files (not shown) to store instructions to be executed by the MEC cell array 66. These register files may utilize a handshaking protocol to fetch the instructions, decode them, and send them to array 66 for further execution. Column processor 74 receives data from the column cells 84 (to be described) after the MEC array 66 completes its calculations. Column processor 74 provides further comparison and processing in deciding which match is the best during the motion vector processing to be described, and subsequently outputs the final motion vector along data line 77, which can be read by the XRISC controller 20 and sent to the VLC 48 for encoding, and subsequently to the DRAM 22.

[0063] Referring to FIG. 4, one embodiment of the MEC array 66 is shown. The MEC cell array 66 is a processor cell array that includes  $7 \times 22 = 154$  cells 68, a portion of which

comprises a sub-array 50 (shown in FIG. 2) having  $5 \times 20 = 100$  cells, each used for processing (i.e., major computing) and referred to as p\_cells 80. MEC array 66 further includes 4 types of boundary cells, namely corner cells 82, column cells 84, updown cells 86 (5 up, 5 down), and io cells 88, which are generally used to store data for use by various components of the MEC engine 38. The interconnections of the p\_cells 80 include 4 inputs and 4 outputs so that data can be transferred to each p\_cell 80 from a neighboring p\_cell 80 in the array 66. One aspect of the present invention is to reduce the complexity of the routing, placement, and layout of logic of the MEC cell array 66. With the embodiment of FIG. 4, this is achieved because each p\_cell 80 of the  $5 \times 20$  sub-array 50 is connected to its neighboring p\_cell 80. This simplifies the logic design complexity to providing adjacent interconnections amongst p\_cells 80. With a simple layout, placement and routing of logic, manufacturing costs of system 10 are reduced, which is particularly beneficial for SoC and ASIC applications.

**[0064]** The interconnections of corner cells 82, 90 and 92 include an input and an output from an adjacent horizontal updown cell 86. The two corner cells 90 and 92 each accept data inputs from the SRAM 60. The interconnections of the column cells 84 include an input and output to an adjacent horizontal p\_cell 80, and an output to the end column processor 74. The interconnections of the updown cells 86 include an input and output to an adjacent vertical p\_cell 80 and two inputs and two outputs to adjacent horizontal cells, which may be two updown cells 86 or a combination of an updown cell 86 and a corner cell 82. The interconnections of an io cell 88 include two pairs of inputs and outputs, one pair for an adjacent horizontal p\_cell 80, and

the other pair for communication with the SRAM 60.

[0065] Each p\_cell 80 can hold several groups of Q pixels for a block. The reference to Q will be described subsequently in more detail. In one embodiment in accordance with the present invention, the p\_cell 80 can hold up to  $Q \times 3$  pixels, including Q pixels from the reference block, Q pixels from the matchblock, and Q pixels from the predicted data. By way of example, if  $Q = 4$ , then p\_cell 80 can hold 12 pixels, comprising 4 continuous pixels in a row of reference data, 4 pixels of matchblock data, and 4 pixels from the prediction (or residue or reconstructed) data. The p\_cell 80 should also be enabled to perform local calculation, as well as concurrently allow data to be moved to another cell. Furthermore, the p\_cell 80 can hold an instruction combined with x-control and a y-control information as will be described in FIG. 5. In this particular implementation of FIG 4, the p\_cells 80 collectively can hold  $20 \times 20$  pixels, since each cell can hold 4 pixels for a block. However, with the addition of the boundary cells 82, 84, 86, and 88, array 66 can hold  $22 \times 22$  pixels, the significance of which will become apparent from the subsequent discussion.

[0066] In particular, io cells 88 enable the input and output of data between SRAM 60 and sub-array 50. For example, the io cells 88 receive image data from the SRAM 60 over datalines 67, and output residual data to the SRAM 60 over datalines 69. Corner cells 82, 90, 92, updown cells 86, column cells 84, and io cells 88 provide boundary storage, which enables data storage when a block of data in the sub-array 50 moves outside of the boundaries of array 66. For

example, if data that is moved upwards from the p\_cells 80 toward the updown cells 86 is not stored in the updown cells 86, it will be lost. By storing data that moves outside of the boundaries (up, down, left, right) of array 66 in these boundary cells, such data can be readily obtained when the previously-moved data re-enters the boundary. Those skilled in the art will appreciate that the accumulation and computational functionality of boundary cells 82, 84, 86, 88, 90 and 92 can be implemented in a variety of ways with conventionally known logic. The boundary cells are further beneficial for increasing the overall memory of the array formed by the p\_cells 80, which is particularly useful for processing a very large frame. Corner cells 82, 90 and 92 provide further memory storage when pixels are moved up, down, left and right.

[0067] In accordance with one embodiment of the present invention, MEC engine 38 interfaces with an external DRAM 22 to obtain picture data and to store processed picture data over databus 36. Picture data read from the DRAM 22 is received by the io cells 88 from the SRAM 60 controlled by SRAM controller 62. This is generally referred to as pre-loading the data. The io cells 88 can shift the data received to the sub-array 50 of p\_cells 80 for processing. The array 66 is enabled to perform calculations on the data received from the io cells 80, and because stream buffer 40 functions as a programmable cache, contemporaneous with such array processing, additional data can be pre-loaded from DRAM 22 into the SRAM 60 for the next set of processing operations. Stream buffer 40 thus enables the MEC array 66 to perform motion estimation processing and when the array 66 is not accessing the stream buffer 40, the stream buffer can pre-fetch data from the memory device 22 for the next MEC operations in parallel.

This parallel processing capability improves the efficiency and speed of the MEC engine 38.

Furthermore, data that is used more than one time by the MEC cell array 66 can be stored in the stream buffer thereby avoiding the need for the memory controllers 24, 26 to load them again from the memory device 22.

[0068] FIG. 5A shows an implementation of the instruction signal distribution for controlling the MEC array 66. X-instruction controller 70 and Y-instruction controller 72 each receive respective control signals over bus 34 from the XRISC controller as shown in FIG 3. The X-instruction controller 70 provides x coordinate control signals to array 66 over lines labeled Xctl\_0, Xctl\_1, Xctl\_2, Xctl\_3, Xctl\_4, and Xctl\_5 as seen in FIG. 5A. The Y-instruction controller 72 provides y coordinate control signals to array 66 over lines labeled Yctl\_0 and Yctl\_1. For example, to provide x coordinate control, 14 bits may be used, and to provide y coordinate control, 21 bits may be used. It will be understood by those skilled in the art that there are a variety of ways to allocate the bits of the control signals to each of the lines Xctl\_0 through Yctl\_1. The particular implementation of FIG. 5A is representative of a Multiple Instruction stream Multiple Data stream (MIMD) architecture that enables multiple cells 68 to each process its own set of control instructions simultaneously and independently of others. For example, MEC cell array 66 has an MIMD control arrangement, each p\_cell 80 can hold different data and be controlled by different instructions. In order to distribute different instructions from the control bus 34 to different p\_cells 80, the present invention separates an instruction into 2 parts, namely x and y. Each part provides partial control of the p\_cell 80. That is, for x-coordinate

control, each row of cell array 66 receives the same x instruction. Moreover, different rows of p\_cells 80 may have different x-instructions, or several rows of p\_cells may receive the same x instruction. While cells 68 of a row may have the same x instruction, each p\_cell 80 in the row receives different y coordinate instruction control. When combining the x and y control in this manner, each cell 68 of array 66 is capable of processing different instructions.

[0069] Referring to FIG. 5B, in an alternate embodiment in accordance with the present invention, the MEC cell array 66 also works suitably-well with a Single Instruction stream Multiple Data stream (SIMD) architecture. With the SIMD architecture, instructions are issued for each operation. Accordingly, instruction controllers 70 and 72 are not required. Rather, the XRISC controller 20 generates WRITE instructions each cycle which pass through x and y instruction elements 94, 96 for controlling the operation of MEC array 66. The SIMD architecture is suited to handle hundreds of instructions issued at the same clock to different cells of the array 66. For example, in the same row of cells 68, the same x coordinate instructions are received, yet each cell 68 of the row receives a different y coordinate instruction. Each successive row is provided with separate instructions for each cell 68. Although the embodiment of the MEC array having control signals with an SIMD arrangement is associated with an increased number of instructions and longer program cycles to achieve the similar results obtained by the MIMD embodiment of FIG. 4A, with a single instruction cycle, multiple instructions may be implemented in the cells. As space constraints become tighter with VLSI, SoC and ASIC applications, one way to keep manufacturing costs low is to use lightweight



processors and to alleviate video processing operations from the XRISC CPU 18. One manner of accomplishing this is by using separate instruction controllers 70 and 72, which are introduced to issue the control instructions to the array 66. Because the embodiment using the MIMD architecture utilizes fewer number of cycles to perform the parallel processing, it is a preferable implementation as it results in the overall speed for video compression being improved, and allows system 10 to be driven by a lightweight low cost processor 18.

[0070] Video compression applied between pictures is facilitated by a process of motion estimation and compensation, wherein a motion vector and difference data is used to specify the translation of a set of picture elements (pels) amongst other pels. The motion estimation technique results in the generation of a motion (estimation) vector (mv). Images of the  $i^{\text{th}}$  picture and the  $i+1^{\text{th}}$  picture are processed by an encoder to determine motion vectors which are the basis for which the  $i+1^{\text{th}}$  and subsequent pictures are encoded for transmission or storage. The bitmaps of the input image are received by the MEC engine 38 in order to derive motion vectors associated with the macroblock data from reference and/or future (subsequent) pictures.

[0071] A motion vector is associated with a matchblock, and represents the relative coordinates in a search area of a reference frame at which a particular matchblock of the current frame may be found. The motion vector indicates the relative two-dimensional translation that the image in the matchblock has undergone relative to its coordinates in the reference block. For example, if a motion vector (-3,3) for the a matchblock is located at the coordinates (24, 20) in

the current frame, then the corresponding image in the search area of the reference frame is found by moving three pixels to the left and three pixels down in the reference frame. Accordingly, the image is located at (21, 23) in the reference frame.

[0072] In block-based motion compensation, a frame of interest being encoded is divided into block of size  $M \times M$ . The motion vector for each matchblock in the current frame is calculated by correlating the matchblock with a corresponding search area in the reference frame. That is, for each block, a search of the previous reconstructed frame is done for the block of size  $M \times M$  that most closely matches the block being encoded. For example, an  $8 \times 8$  matchblock may be scanned pixel-by-pixel relative to a  $20 \times 20$  search area in the reference frame. This process can be analogized to having the matchblock overlaid at an initial position within the search area of the reference frame. A matchblock/search area correlation error between the pixel intensity values of the matchblock and the overlaid search area can then be determined. Several techniques may be employed to determine the error measurement therebetween, for example, by determining the mean absolute error or the mean square error. An exhaustive search is typically then performed wherein the matchblock may then be moved one pixel horizontally or vertically within the search area of the reference frame, so that the error at that position can be calculated. This process continues until the error between the matchblock and the search area has been calculated for every position within the search area. A minimum error for all positions is indicative of the highest correlation between the matchblock of the current frame and the search area of the reference frame. The x- and y-coordinate translation of the position of the search area

associated with the minimum error is selected as the motion vector for the corresponding matchblock. As such, the term "motion vector" may generally refer to any x and y coordinate translation vector for the search area. When the encoder transmits the reference frame, instead of transmitting subsequent frames, the motion vectors can be transmitted thereby to save time and bandwidth, at least until another reference frame of a source image must be transmitted. Thereafter, motion vectors may be transmitted as before.

[0073] An aspect in accordance with the present invention is to determine the motion vector in manner that avoids the large computations conventionally associated with performing the exhaustive search of a search area with the matchblock. It is further desirable to reduce the large number of calculations traditionally involved to determine the motion vector in a manner that will improve the accuracy of motion estimation or maintain a high quality of motion compensation. Accordingly, the operation of the present invention will be described in detail with reference to FIG. 6. Rather than performing the conventional exhaustive search of the macroblock with a large search area, the present invention describes a three-stage multi-resolution search followed by YUV estimation and decompensation.

[0074] As shown in FIG. 6, the process 100 of motion estimation and compensation starts with a partial pixel level search 102, followed by a full pixel level search 104, a fractional pixel search 106, YUV estimation 108 and decompensation 110. Each of these functions will be further described with reference to the flowchart of FIG. 7. At times during the discussion,

reference will be made to FIGs. 9, and 10A-C for illustrative purposes.

[0075] In performing the step of partial pixel level searching 102, searches on a smaller picture size (i.e., subsampled pixels) are performed to determine a preliminary motion vector ( $mv_{Q \times Q}$ ) 232. In particular, an  $M \times M$  pixel-sized matchblock 220 (e.g., macroblock) of a current frame is decomposed 112 (i.e., subsampled) into a smaller size picture, denoted by a sub-matchblock 226 of size  $Q \times Q$ , where  $Q < M$ . At times, reference to  $Q \times Q$  will be made to  $Q^2$ , primarily for convenience. For example, if  $M = 16$ , and  $Q = 4$ , then a  $16 \times 16$  block is split into four  $4 \times 4$  sub-matchblocks to find the preliminary motion vector  $mv_{Q \times Q}$  232 for each  $4 \times 4$  block. This effectively decomposes the original picture into smaller sub-sampled pictures from which to interpolate data. For example, if the current frame is  $640 \times 480$  pixels, then a  $Q^2$  size search can be selected to be  $4 \times 4$ , thereby resulting in a block of  $160 \times 120$  pixels. Each pixel of the  $Q^2$  size picture is the average of every 16 pixels forming the original picture. With substep 112, the sub-matchblock will be  $4 \times 4$ , instead of  $16 \times 16$ . Similarly, the search area 222 of the reference frame 224 is decomposed 114 by a factor of  $Q$  into search area sub-blocks 228, so that an exhaustive  $Q^2$  search can be performed in the (modified) search area sub-blocks 228. In substep 116, the  $Q^2$  size ( $4 \times 4$ ) matchblock data 226 is loaded 116 into the cell array 66, and distributed, that is duplicated to 16 identical ones across each sub-block 228, as seen in FIG. 9A.

[0076] Referring to FIG. 9, a matchblock 220 is typically scanned over a corresponding search area 222 within a reference frame 224 to find the best match. This process is repeated for

each matchblock in the search area 222. By contrast, when performing the  $Q^2$  search of the present invention, several sub-tasks may be performed in parallel. For example, referring back to FIG. 10A, the matchblock 220 has been split (subsampling) into  $Q \times Q$  sub-matchblocks 226. Similarly, the search area 222 has been split into  $4 \times 4$  sub-blocks 228, each of  $16 \times 16$  pixels. Using the MEC cell array 66 of the present invention, within a (e.g.,  $16 \times 16$ ) search area sub-block 228, the  $Q \times Q$  pixel sub-matchblock 226 can be duplicated as each sub-matchblock 226 is of size  $4 \times 4$ . This duplication can be repeated 16 times over the search area sub-blocks 228. Each of the 16 sub-matchblocks 226 can then be searched in parallel using reduced size (e.g.,  $7 \times 7$ ) sub-search areas 130. Also in substep 116, the  $Q^2$  size reference area is loaded into cell array 66. By way of example, the search is performed on a  $4 \times 4$  sub-matchblock 226 in a  $19 \times 19$  area, which is selected as a reasonably large sub-search area. Accordingly, a total of  $16 \times 16$  matches are needed. Amongst the 16 sub-matchblocks 226, each being of  $4 \times 4$  pixels, for each sub-matchblock 226, only  $(16 \times 16) / 16 = 16 = 4 \times 4$  matches are needed. For a  $Q \times Q = 4 \times 4$  sub-matchblock in a  $4 \times 4$  search, the search area will be  $7 \times 7$ . For B-type frames, the search area 222 is typically  $73 \times 73$  pixels for previous and post reference frames, while with P-type frames, the search area is typically  $153 \times 73$  pixels for left and right parts of the reference frame.

[0077] In order to use the previous frame to predict the pixel values in the current frame being encoded, a calculation of the partial sum of the absolute distance  $Psad$  (or SAD) is undertaken as follows. For each identical  $Q^2$  size sub-matchblock 226, the  $Psad$  is determined 118, as defined by Eq. (1), wherein  $match_{i,j}$  represents the location of a pixel in the matchblock

226, and  $ref_{i,j}$  represents a location of a pixel in the reference area. As part of substep 118, the partial results (of the SAD of all 4 pairs of pixels in one row) is collected and transferred to the end column processor 74 as part of the motion search. In the particular embodiment, a total of 16 output wires are used.

$$P_{sad_{i,j}} = \sum_{i,j=0..3} |match_{i,j} - ref_{i,j}|; \quad (1)$$

[0078] One manner of implementing this transfer is with a calling procedure to the RISC CPU 18 coordinated by controller 20. Thereafter, substep 120 is undertaken to move the reference sub-search area 230 so that continuing SAD calculations can be performed as part of the exhaustive search in the  $Q^2$  size level search. Once these steps are performed, the best match preliminary motion vector  $mv_{Q \times Q}$  232 can be found 122 relative to the center 234 of the search area 222, indicating how many pixels in the y direction and how many pixels in the x direction is the best match displaced in the next picture relative to the reference picture. The sub-process described by substeps 112-122 effectively reduces the size of all frames (current and reference), as well as the matchblock and the search area by a quarter of the size of the original frame, i.e., from 16 x 16 to 4 x 4. As will be understood, an exhaustive search is still undertaken, but the calculations rapidly decreases. For example, for each sub-matchblock 226 and search area sub-block 228, the calculation is 16, and no longer 256. Because the matchblock is 1/16th the size of the original picture, and because the search range is 1/16th of the original size, the overall calculation is reduced by 1/56th of the original motion vector calculation. The resulting preliminary motion vector  $mv_{Q \times Q}$  232 determined relative to the center 234 of search area 222,

however, will typically need further refinement. For discussion purposes, we will assume a  $mv_{Q \times Q}$  of (4, 8) has been determined using the  $Q^2$  search.

[0079] To obtain further precision of the motion vector, the MEC process 100 undertakes a full pixel level search 104 for determining an intermediate motion vector  $mv_{full}$ . Still referring to FIG. 7, step 104 includes a substep 124, wherein the full size (16 x 16) matchblock data as well as the current frame are loaded into cell array 66. Those skilled in the art will understand that as a point of reference, the motion vector is obtained by subtracting the location of the upper-left corner of the block being encoded from the location of the upper-left corner of the block in the search area that is the best match. Because a preliminary motion vector,  $mv_{Q \times Q}$  232, has been already determined, a search in the entire reference area is unnecessary. Rather, a search can be performed within a small area around the preliminary motion vector,  $mv_{Q \times Q}$  232. Accordingly and as shown in FIG. 10C, a refined reference search area 240 is determined and loaded 126 in cell array 66. To determine the refined search area 240, an additional search range (e.g.,  $\pm 2$ ) is selected to increase the search area 222 from a 16 x 16 block to a 20 x 20 block. The refined search area 240 is loaded in cell array 66. A refinement range of  $\pm 2$  can be selected based on the  $Q^2$  size search because the search space and the match space were sub-sampled into a 4 x 4 block from a 16 x 16 block. The resulting  $mv_{Q \times Q}$  232 actually represents a granularity of 4 pixel positions in the 16 x 16 dimension block 222, since in order to perform the  $Q^2$  search, a block of  $4 \times 4 = 16$  pixels were sub-sampled into 1 pixel. So when a motion vector  $mv_{Q \times Q}$  232 is found relative to the  $Q^2$  search, the corresponding vector in the M x M dimension block actually lies

within 4 possible pixels of the  $mv_{Q \times Q}$ . The algorithm of the present invention presupposes that each pixels in the  $Q \times Q$  search stands for 4 pixels in the  $M \times M$  dimension, and that the  $mv_{Q \times Q}$  232 is in the center of the block, so a  $\pm 2$  addition to the search range is a refinement of the granularity. For example, the preliminary motion vector  $mv_{Q \times Q}$ , (4,8), in the previous example, translates to (16, 32), and can be refined as  $(16 \pm 2, 32 \pm 2) = (20, 36)$ . In order to use the previous frame to predict the pixel values in the current frame being encoded, a calculation of the SAD 128 is undertaken as described with Eq. (2) to determine whether the match is acceptable. As part of substep 128, the partial result (i.e., the SAD of all 16 pairs of pixels in one row) is collected and transferred to the end column processor 74. In the particular embodiment, a total of 20 output wires are used.

$$Psad_{i,j} = \sum_{i,j=0..15} | match_{i,j} - ref_{i,j} | ; \quad (2)$$

[0080] One manner of implementing this transfer is with a calling procedure to the RISC CPU 18 coordinated by controller 20. Thereafter, substep 130 is undertaken to move the matchblock relative to the refined search area 240 and so that continuing SAD calculations can be performed as part of the exhaustive search in the full size (20 x 20) level search. In FIG. 10B, a distance 144 of  $\pm 2$  around the pixel location 245 indicated by  $mv_{Q \times Q}$  232 is a 5 x 5 pixel sub-array 242. Accordingly, a total computation of  $5 \times 5 = 25$  matches are undertaken, where each match has  $16 \times 16 = 256$  calculations performed as part of the exhaustive search. Once these steps are performed, the best match intermediate motion vector  $mv_{full}$  246 can be found 132, indicating how many pixels in the y direction and how many pixels in the x direction is the best



match displaced in the current picture relative to the reference picture. It will become apparent to those skilled in the art that with the substeps 124-132, the full size search attempts to improve the motion estimation of step 102, that is, by determining a full pixel level motion vector,  $mv_{full}$  246, which is a refinement of the  $mv_{QxQ}$  232. By way of example, the preliminary motion vector  $mv_{QxQ} = (4, 8)$  might be further refined to (5,6) with step 104.

[0081] With the above steps 102 and 104, one object of the present invention is to reduce the number of calculations involved in processing the motion vector data. As it will be evident from the description above, the  $Q^2$  search reduces the motion estimation process by 1/56th, while the full size search further reduces the search to a small range around the preliminary motion vector. It will be understood that at each level of the motion estimation calculation from steps 102 and 104, the number of calculations conventionally associated with motion estimation is reduced, as is the complexity of calculations typically required.

[0082] For example, referring to FIG. 10A, for one sub-matchblock 226 in a search area sub-block 228, there is a 4:1 sub-sampled representation. Because such search area sub-block 228 is a 16 x 16 pixel area in which to search for sub-matchblock 226, which is 4 x 4 pixels in size, the exhaustive search for one match involves undertaking 16 comparisons (differences) 16 calculations involving computing the absolute value of the differences; and 15 additions of the 16 values. So, for (16x16 =) 256 matches in the search area 122, the total computations involved is  $256 \bullet 16$  comparisons +  $256 \bullet 16$  absolute values +  $256 \bullet 15$  additions. This is a significant

reduction in the number of calculations by comparison to conventional methods of using the matchblock to exhaustively search the entire search area. When the full pixel level search is undertaken to refine the granularity of the preliminary motion vector  $mv_{QxQ}$  232, the computation will be based on 25 matches. So, even though there are additional stages associated with refining the motion vector in accordance with the present invention, the overall number of calculations is significantly reduced.

[0083] Referring back to FIG. 7, to obtain the prediction data and residual data to be quantized, the MEC process 100 undertakes a fractional pixel level search 106 to further improve the precision of the intermediate motion vector  $mv_{full}$  246. In one embodiment in accordance with the present invention, the fraction utilized corresponds to a half pixel search. With this particular embodiment, the displacement between current and reference frames is measured in half pixels. Pixels of the coded frame being search are interpolated to obtain twice the number of pixels as in the original frame to obtain a double image. This doubled image can then be searched for the best matching block.

[0084] At substep 134, the 16 x 16 matchbock (e.g., macroblock) is located at a point of reference in the current frame, while at substep 136, a refined reference area, based on the result of the full size search, is located at a point of reference and calibrated with the point of reference for the macroblock. The half pixel calculation is then determined 138.

[0085] Referring now to the image in FIG. 8, the half pixel calculation will now be

described. In FIG. 8, A, B, C, D, E, F, G, H and I represent the pixels of the image in the original frame. The half-pixels h1, h2, h3, h4, h5, h6, h7 and h8 may be determined by interpolating adjacent original pixels by the following equations. The half pixels of Equations (3) through (6) are determined by interpolating between adjacent two neighboring pixels, while the half pixels of Equations (7) through (10) are determined from the average of the four neighboring pixels. It will be understood by those skilled in the art that if the results of Eq.s (3) through (10) are not desired in a floating point data form then a value of 0.5 may be added to each of these equations to provide a rounded final value.

$$h_2 = (B + E)/2 \quad (3)$$

$$h_4 = (D + E)/2 \quad (4)$$

$$h_5 = (E + F)/2 \quad (5)$$

$$h_7 = (E + H)/2 \quad (6)$$

$$h_1 = (A + B + D + E)/4 \quad (7)$$

$$h_3 = (B + C + E + F)/4 \quad (8)$$

$$h_6 = (D + E + G + H)/4 \quad (9)$$

$$h_8 = (E + F + H + I)/4 \quad (10)$$

**[0086]** In order to complete step 138, a half-pixel predicted reference macroblock  $\text{pred}_{i,j}$  is determined according to Eq. (11).

$$\begin{aligned} \text{pred}_{i,j} = & \\ & (\text{ref}_{i,j} + \text{ref}_{i,j-1} + 1) \gg 1; \text{ or} \\ & (\text{ref}_{i,j} + \text{ref}_{i,j+1} + 1) \gg 1; \text{ or} \\ & (\text{ref}_{i,j} + \text{ref}_{i-1,j} + 1) \gg 1; \text{ or} \\ & (\text{ref}_{i,j} + \text{ref}_{i+1,j} + 1) \gg 1; \text{ or} \\ & (\text{ref}_{i,j} + \text{ref}_{i,j-1} + \text{ref}_{i-1,j} + \text{ref}_{i-1,j-1} + 2) \gg 2; \text{ or} \\ & (\text{ref}_{i,j} + \text{ref}_{i,j-1} + \text{ref}_{i+1,j} + \text{ref}_{i+1,j-1} + 2) \gg 2; \text{ or} \\ & (\text{ref}_{i,j} + \text{ref}_{i,j+1} + \text{ref}_{i+1,j} + \text{ref}_{i+1,j+1} + 2) \gg 2; \text{ or} \\ & (\text{ref}_{i,j} + \text{ref}_{i,j+1} + \text{ref}_{i-1,j} + \text{ref}_{i-1,j+1} + 2) \gg 2 \end{aligned} \quad (11)$$

[0087] In order to use the previous frame to predict the pixel values in the current frame being encoded, a calculation of the partial SAD 140 is undertaken according to Eq. (12) to determine whether the match is acceptable. As part of substep 140, the partial result (i.e., the SAD of all 16 pairs of pixels in one row) is collected and transferred to the end column processor 74. In the particular embodiment, a total of 20 output wires are used.

$$P_{sad_{ij}} = \sum_{i,j=0..15} | match_{ij} - pred_{ij} | \quad (12)$$

[0088] Thereafter, substep 142 is undertaken to move the matchblock so that continuing the calculation of prediction data  $pred_{ij}$  and SAD can be performed for the half-pixel search on all 8 of the positions, h1, h2, h3, h4, h5, h6, h7 and h8, since there are 8 half pixel possible predictions around a pixel. FIG. 10C illustrates the effect of these calculations to improve the granularity of the intermediate motion vector  $mv_{full}$  246 to  $mv_{final}$  250. By way of example, the preliminary motion vector  $mv_{QxQ} = (4, 8)$  that was refined to (5,6), can be further refined to create the prediction data (5, 6.5).

[0089] One aspect of the present invention is to reduce the number of motion estimation calculations while keeping a high quality of the resulting predictions. In addition to decreasing the number of calculations for motion estimation as already described, the present invention improves motion estimation processing by incrementally improving the resolution of the motion vector from the three stages involving partial pixel level search, full pixel level search and the half pixel search. Additionally, with the half pixel level search, no more new data need be

loaded from DRAM 22 into the MEC array 66 because the necessary data was already loaded during full size search step 104. For example, even though the full size search required a 20 x 20 block, the array 66 can accommodate 22 x 22 blocks, thereby storing other image data in the various boundary cells for use in the half pixel search stage.

[0090] The process 100 continues with the YUV estimation step 108. This subprocess comprises locating the matchblock and reference block in the SRAM 60, and loading them from the stream buffer 40 into the MEC array 66 in order to facilitate U (8 x 8) and V (8 x 8) estimation. It will be understood by those skilled in the art of video processing, that the step of loading data into the array 66 includes placing the image in the array at a point of reference, e.g., either to the right or in a vertically centered position. The matchblock  $match_{ij}$  and reference block for the luminance, Y, has already been loaded into the array during the full size search. With the prediction data,  $pred_{ij}$ , determined from the half pixel search, the predicted data of the reference (16 x 16) matchblock can be computed using Eq. (13).

$$\begin{aligned}
 pred_{ij} = & \\
 & ref_{ij} ; \text{ or} \\
 & (ref_{ij} + ref_{i,j-1} + 1) \gg 1; \text{ or} \\
 & (ref_{ij} + ref_{i,j+1} + 1) \gg 1; \text{ or} \\
 & (ref_{ij} + ref_{i-1,j} + 1) \gg 1; \text{ or} \\
 & (ref_{ij} + ref_{i+1,j} + 1) \gg 1; \text{ or} \\
 & (ref_{ij} + ref_{i,j-1} + ref_{i-1,j} + ref_{i-1,j-1} + 2) \gg 2; \text{ or} \\
 & (ref_{ij} + ref_{i,j-1} + ref_{i+1,j} + ref_{i+1,j-1} + 2) \gg 2; \text{ or} \\
 & (ref_{ij} + ref_{i,j+1} + ref_{i+1,j} + ref_{i+1,j+1} + 2) \gg 2; \text{ or} \\
 & (ref_{ij} + ref_{i,j+1} + ref_{i-1,j} + ref_{i-1,j+1} + 2) \gg 2
 \end{aligned} \tag{13}$$

[0091] The residual data,  $residue_{ij}$ , of the macroblock can then be determined from Eq. (14).

$$\text{residue}_{i,j} = \text{match}_{i,j} - \text{pred}_{i,j} \quad (14)$$

$i,j = 0..15$

[0092] The prediction macroblock,  $\text{pred}_{i,j}$ , and the residue macroblock,  $\text{residue}_{i,j}$ , may be output to stream buffer 40 through the io cells 88, and over data lines 69.

[0093] In general, once the residue and prediction data are determined for a macroblock, such information is typically stored (e.g., WRITE) to the memory device 22, so that the previously described process can be performed on the next macroblock. After several macroblocks have been processed in this manner or periodically, data is received from the IDCT 42 by the MEC array 66 so that decompensation (step 110) can be performed to reconstruct the video stream that will be coded. To perform decompensation, the residue data  $\text{residue}_{i,j}$  and prediction data  $\text{pred}_{i,j}$  of the Y (16 x 16), U (8 x 8) and V (8 x 8) components are located in memory and reloaded into the array 66. Reconstruction of the macroblock data can be implemented using Eq. (15).

$$\text{reconstructed}_{i,j} = \text{residue}_{i,j} + \text{pred}_{i,j} \quad (15)$$

$i,j = 0..15$

[0094] The reconstructed macroblock,  $\text{reconstructed}_{i,j}$ , can be output to the stream buffer 40 through the io cells 88, and over data lines 69.

[0095] With the present invention, real time encoding can be implemented at 20 x 480 x 30 frames per second, by way of example. However, even though the MEC array 66 of FIG. 3 has been described with respect to the specific architecture of system 10 in FIG. 2, it will be

appreciated that MEC array 66 may work suitably well with other architectures of video compression systems. For example, the MEC engine 38 can be used as an MPEG codec. Further, the MEC array 66 has a wider application than the motion estimation techniques described herein. Similarly, MEC array 66 is not limited to only performing the sequence of steps described in FIGs. 6-7 with regard to motion estimation. Those skilled in the art will understand that the MEC array 66 may operate suitably well with other sequences of steps and functions to provide video compression.

[0096] After reviewing this disclosure, those skilled in the art will recognize that the present invention applies not only to motion vectors determined according to the pixel-by-pixel technique described above, but may be extended to motion vectors found with other schemes. Furthermore, it will be appreciated by those of ordinary skill in the art that the present invention may be practiced in a variety of ways and is applicable to video standards following ISO MPEG, MPEG-1, MPEG-2, MPEG-4, H.261, H.263, H.323 standards, as well as the ITU-Telecom H.262.

[0097] Although the invention has been described in considerable detail with reference to certain embodiments, other embodiments are possible. As will be understood by those of skill in the art, the invention may be embodied in other specific forms without departing from the essential characteristics thereof. Accordingly, the present invention is intended to embrace all such alternatives, modifications and variations as fall within the spirit and scope of the appended

26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147 148 149 150 151 152 153 154 155 156 157 158 159 160 161 162 163 164 165 166 167 168 169 170 171 172 173 174 175 176 177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195 196 197 198 199 200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232 233 234 235 236 237 238 239 240 241 242 243 244 245 246 247 248 249 250 251 252 253 254 255 256 257 258 259 260 261 262 263 264 265 266 267 268 269 270 271 272 273 274 275 276 277 278 279 280 281 282 283 284 285 286 287 288 289 290 291 292 293 294 295 296 297 298 299 300 301 302 303 304 305 306 307 308 309 310 311 312 313 314 315 316 317 318 319 320 321 322 323 324 325 326 327 328 329 330 331 332 333 334 335 336 337 338 339 340 341 342 343 344 345 346 347 348 349 350 351 352 353 354 355 356 357 358 359 360 361 362 363 364 365 366 367 368 369 370 371 372 373 374 375 376 377 378 379 380 381 382 383 384 385 386 387 388 389 390 391 392 393 394 395 396 397 398 399 400 401 402 403 404 405 406 407 408 409 410 411 412 413 414 415 416 417 418 419 420 421 422 423 424 425 426 427 428 429 430 431 432 433 434 435 436 437 438 439 440 441 442 443 444 445 446 447 448 449 450 451 452 453 454 455 456 457 458 459 460 461 462 463 464 465 466 467 468 469 470 471 472 473 474 475 476 477 478 479 480 481 482 483 484 485 486 487 488 489 490 491 492 493 494 495 496 497 498 499 500 501 502 503 504 505 506 507 508 509 510 511 512 513 514 515 516 517 518 519 520 521 522 523 524 525 526 527 528 529 530 531 532 533 534 535 536 537 538 539 540 541 542 543 544 545 546 547 548 549 550 551 552 553 554 555 556 557 558 559 560 561 562 563 564 565 566 567 568 569 570 571 572 573 574 575 576 577 578 579 580 581 582 583 584 585 586 587 588 589 590 591 592 593 594 595 596 597 598 599 600 601 602 603 604 605 606 607 608 609 610 611 612 613 614 615 616 617 618 619 620 621 622 623 624 625 626 627 628 629 630 631 632 633 634 635 636 637 638 639 640 641 642 643 644 645 646 647 648 649 650 651 652 653 654 655 656 657 658 659 660 661 662 663 664 665 666 667 668 669 670 671 672 673 674 675 676 677 678 679 680 681 682 683 684 685 686 687 688 689 690 691 692 693 694 695 696 697 698 699 700 701 702 703 704 705 706 707 708 709 710 711 712 713 714 715 716 717 718 719 720 721 722 723 724 725 726 727 728 729 730 731 732 733 734 735 736 737 738 739 740 741 742 743 744 745 746 747 748 749 750 751 752 753 754 755 756 757 758 759 760 761 762 763 764 765 766 767 768 769 770 771 772 773 774 775 776 777 778 779 780 781 782 783 784 785 786 787 788 789 790 791 792 793 794 795 796 797 798 799 800 801 802 803 804 805 806 807 808 809 810 811 812 813 814 815 816 817 818 819 820 821 822 823 824 825 826 827 828 829 830 831 832 833 834 835 836 837 838 839 840 841 842 843 844 845 846 847 848 849 850 851 852 853 854 855 856 857 858 859 860 861 862 863 864 865 866 867 868 869 870 871 872 873 874 875 876 877 878 879 880 881 882 883 884 885 886 887 888 889 890 891 892 893 894 895 896 897 898 899 900 901 902 903 904 905 906 907 908 909 910 911 912 913 914 915 916 917 918 919 920 921 922 923 924 925 926 927 928 929 930 931 932 933 934 935 936 937 938 939 940 941 942 943 944 945 946 947 948 949 950 951 952 953 954 955 956 957 958 959 960 961 962 963 964 965 966 967 968 969 970 971 972 973 974 975 976 977 978 979 980 981 982 983 984 985 986 987 988 989 990 991 992 993 994 995 996 997 998 999 1000 1001 1002 1003 1004 1005 1006 1007 1008 1009 1010 1011 1012 1013 1014 1015 1016 1017 1018 1019 1020 1021 1022 1023 1024 1025 1026 1027 1028 1029 1030 1031 1032 1033 1034 1035 1036 1037 1038 1039 1040 1041 1042 1043 1044 1045 1046 1047 1048 1049 1050 1051 1052 1053